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$Z+$ Jets Cross Section Ratio Measurements

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Abstract. We present a study of events with Z bosons and jets produced at the Fermilab Tevatron Collider in $p\overline{p}$ collisions at a center of mass energy of 1.96 TeV. The data sample consists of nearly 14,000 $Z/\gamma^* \rightarrow e^+e^-$ candidates corresponding to the integrated luminosity of 340 pb^{-1} collected using the DØ detector. Ratios of the $Z/\gamma^* + \geq n$ jet cross sections to the total inclusive Z/γ^* cross section have been measured for $n = 1$ to 4 jet events. Our measurements are found to be in good agreement with a next-to-leading order QCD calculation and with a tree-level QCD prediction with parton shower simulation and hadronization.

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INTRODUCTION

Leptonic decays of the electroweak gauge bosons, $W^{\pm}$ and Z, produced in association with jets are prominent signatures at present and future hadron colliders. Measurements of $W/Z + \geq n$ jet cross sections are important for understanding perturbative quantum chromodynamics (QCD) calculations and for developing Monte Carlo (MC) simulation programs capable of handling partons in the final state at leading order (LO), or in some cases, next-to-leading order (NLO). Furthermore, the associated production of W/Z bosons with jets represents a significant background to Higgs boson searches, as well as other standard model processes of interest such as top quark production, and many new physics searches at the Fermilab Tevatron Collider and the CERN Large Hadron Collider.

In this study, we present the first measurement of the ratios of the $Z/\gamma^* + \geq n$ jet production cross sections to the total inclusive Z/γ^* cross section for jet multiplicities $n = 1-4$ in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. These results are based on a data sample corresponding to an integrated luminosity of 340 pb^{-1} accumulated with the DØ detector [1].

EVENT SELECTION

The data sample for this analysis [2] was collected between April 2002 and June 2004. Events from $Z/\gamma^* \rightarrow e^+e^-$ decays were selected with a combination of single-electron triggers, based on energy deposited in calorimeter towers ($\Delta\eta \times \Delta\phi = 0.2 \times 0.2$). Final event selection was based on detector performance, event properties, and electron and jet identification criteria.

Events were required to have a reconstructed primary vertex with a longitudinal position within 60 cm of the detector center. Electrons were reconstructed from electromagnetic (EM) clusters in the calorimeter using a simple cone algorithm. The two highest-p_T electron candidates in the event, both having transverse momenta $p_T > 25$ GeV, were used to reconstruct the Z boson candidate. Both electrons were required to be in the central region of the calorimeter $|\eta_{\mathrm{det}}| < 1.1$ (pseudorapidity η_{det} is calculated with respect to the center of the detector) with at least one of the electrons having fired the trigger(s) for the event. The electron pair was required to have an invariant mass consistent with the Z boson mass, 75 GeV $< M_{ee} <$ 105 GeV.

To reduce background contamination, mainly from jets misidentified as electrons, the EM clusters were required to pass additional quality criteria based on the shower profile. Additionally, at least one of the electrons was required to have a spatially matched track associated with the reconstructed calorimeter cluster, and the track momentum had to be consistent with the energy of the EM cluster. A total of 13,893 events passed the selection criteria.

Jets were reconstructed using the “Run II cone algorithm" [3] which combines particles within a cone of radius $R_{\mathrm{cone}} = 0.5$. Spurious jets from isolated noisy calorimeter cells were eliminated by cuts on the jet energy deposition pattern. Jets were required to be confirmed by energy deposits as measured by the trigger readout. The transverse momentum of each jet was corrected for multiple $p\bar{p}$ interactions, calorimeter noise, out–of–cone showering effects, and energy response of the calorimeter as determined from the missing transverse energy balance of photon–jet events. Jets were required to have $p_T > 20$ GeV and $|\eta| < 2.5$; jets were eliminated if they overlapped with the electrons coming from the Z boson decay within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$. Small jet losses due to this separation cut from the Z boson electrons were estimated as a function of the number of associated jets using a PYTHIA [4] event generator MC sample.

BACKGROUNDS

The primary source of background to the Z/γ^* dielectron signal is from multijet production from QCD processes in which the jets have a large electromagnetic component or they are mismeasured in some way that causes them to pass the electron selection criteria. There are also contributions to the Z/γ^* candidates that are not from misidentification of electrons, but correspond to standard model processes (e.g., $t\bar{t}$ production, $Z \to \tau^+\tau^-$, $W \to e\nu$). Such irreducible background contributions were taken into account, but found to be small.

CROSS SECTION RATIOS

The cross sections as a function of jet multiplicity were corrected for jet reconstruction and identification efficiencies, and for event migration due to the finite jet energy resolution of the detector. The fully corrected ratios, R_n, of the $Z/\gamma^* + \geq n$ jet production cross sections to the inclusive Z/γ^* cross section

$$R_n \equiv \frac{\sigma(Z/\gamma^* + \geq n \text{ jets})}{\sigma(Z/\gamma^*)} \tag{1}$$

TABLE 1. Cross-section ratios with statistical and systematic uncertainties (all $\times 10^{-3}$) for different inclusive jet multiplicities.

Multiplicity ($Z/\gamma^* + \geq n$ jets)	≥ 1	≥ 2	≥ 3	≥ 4
R_n	120.1	18.6	2.8	0.90
Total Statistical Uncertainty	± 3.3	± 1.4	± 0.56	± 0.44
Total Systematic Uncertainty	$-17.1, +15.6$	$-5.0, +6.2$	$-1.06, +1.43$	$-0.40, +0.48$
Jet Energy Calibration	± 11.7	± 3.3	± 0.74	± 0.23
Jet Reconstruction/Identification	$-7.0, +2.2$	$-2.9, +4.3$	$-0.64, +0.82$	$-0.30, +0.40$
Unsmearing Procedure	$-3.6, +2.2$	$-1.6, +2.4$	$-0.24, +0.85$	$-0.08, +0.09$
Jet Energy Resolution	$-2.7, +3.4$	$-0.04, +0.13$	$-0.17, +0.15$	$-0.03, +0.04$
Acceptance	± 1.8	± 0.7	± 0.10	± 0.003
Efficiencies (Trigger, EM, Track)	± 8.5	± 1.3	± 0.20	± 0.07
Electron-Jet-Overlap	± 3.2	± 0.7	± 0.14	± 0.05

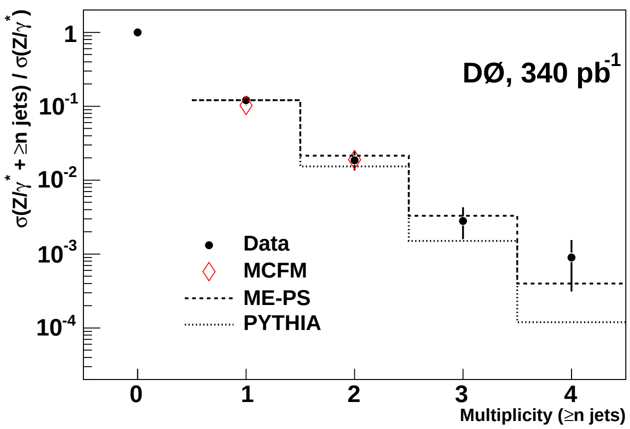

FIGURE 1. Ratios of the $Z/\gamma^* + \geq n$ jet cross sections to the total inclusive Z/γ^* cross section versus jet multiplicity. The uncertainties on the data points (dark circles) include the combined statistical and systematic uncertainties added in quadrature. The dashed line represents the predictions of LO Matrix Element (ME) calculations using PYTHIA for parton showering (PS) and hadronization, normalized to the measured $Z/\gamma^* + \geq 1$ jet cross-section ratio. The dotted line represents the predictions of PYTHIA normalized to the measured $Z/\gamma^* + \geq 1$ jet cross-section ratio. The open diamonds represent the MCFM predictions.

for the mass region 75 GeV $< M_{ee} <$ 105 GeV are summarized in Table 1. Systematic uncertainties include contributions from the jet energy calibration corrections, jet reconstruction and identification efficiency, unsmearing procedure, jet energy resolution, and variations in the acceptance coming from samples with different event generators. They also take into account uncertainties in the variation of efficiencies for trigger, electron reconstruction, identification, and track matching as a function of jet multiplicity, as well as uncertainties due to the electron-jet overlap correction. All these uncertainties are assumed to be uncorrelated and they are added in quadrature to estimate the total systematic uncertainty. The statistical uncertainties include contributions from the number of candidate events, background estimation, acceptance, efficiencies, and unsmearing correction.

Figure 1 shows the fully corrected measured cross-section ratios for $Z/\gamma^*+\geq n$ jets as a function of jet multiplicity, compared to three QCD predictions. MCFM [5] is a NLO calculation for up to Z/γ^*+2 parton processes. The CTEQ6M [6] parton distribution function (PDF) set was used, and the factorization and renormalization scales $\mu_{F/R}$ were set to the Z boson mass, M_Z. ME-PS was based on MADGRAPH [7] Z/γ^*+n LO Matrix Element (ME) predictions using PYTHIA for parton showering (PS) and hadronization, and a modified CKKW [8] method to map the Z/γ^*+n parton event into a parton shower history [9]. The ME-PS predictions were produced with MADGRAPH tree level processes of up to three partons and have been normalized to the measured $Z/\gamma^*+\geq 1$ jet cross-section ratio. The CTEQ6L PDF set was used, and the factorization scale was set to $\mu_F = M_Z$. The renormalization scale was set to $\mu_R = p_{T\,jet}$ for jets from initial state radiation and $\mu_R = k_{T\,jet}$ for jets from final state radiation ($k_{T\,jet}$ is the transverse momentum of a radiative jet relative to its parent parton momentum direction). The PYTHIA predictions have been normalized to the measured $Z/\gamma^*+\geq 1$ jet cross-section ratio. The CTEQ5L [10] PDF set was used, and the factorization and renormalization scales were set to $\mu_{F/R} = M_Z$. The MCFM and ME-PS predictions are generally in good agreement with the data. PYTHIA predicts fewer events with high jet multiplicity due to missing higher order contributions at the hard-scatter level.

CONCLUSIONS

In summary, we have presented the first measurements of the ratios of the $Z/\gamma^*+\geq n$ jet ($n = 1-4$) production cross sections to the total inclusive Z/γ^* cross section from $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The measured ratios of cross sections were found to be in good agreement with MCFM and an enhanced leading-order matrix element prediction with PYTHIA-simulated parton showering and hadronization. PYTHIA simulations alone exhibit a deficit of high jet multiplicity events.

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